TLEP, first step in a long-term vision for HEP

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Abstract

TLEP is an e^+e^- storage ring collider that could fit in a new 80-km tunnel as precursor/companion of a 100 TeV hadron collider, as a first step in a long term vision. It covers the centre-of-mass energy range from the Z peak to the top quark pair threshold (350 GeV). Compared to other projects of similar timescale and cost, it offers higher performance by a factor 30 (at 240 GeV) to 1000 (at the Z peak). This allows determination with unprecedented precision of the properties of the recently discovered H(126) scalar boson, and of quantities (m_t, m_W, m_Z, etc) sensitive to electroweak radiative corrections, thus providing stringent tests of the closure of the Standard Model. A design study, recommended in the proposed European Strategy for Particle Physics, is undertaken in a global framework, with the aim of producing a conceptual design study report within two years, followed by a technical design by 2017. This will enable the community to make an informed decision, based also on the results of LHC at nominal energy. Assuming a positive decision, construction could begin in the early 2020's.

Introduction

The discovery of H(126) is a triumph of the Standard Model (SM). The mass of this Higgs boson candidate is consistent with expectations from precision measurements assuming no new physics, but also with those of a number of extensions of the SM invoked to solve the hierarchy problem. It is also consistent with straightforward extrapolation to the Planck scale, so that the need for new physics at the TeV scale is a totally open question.

On a more practical side, the H(126) mass is low enough to allow detailed studies to be carried out with an e^+e^- collider operating near the ZH production maximum, 240GeV centre-of-mass (E_{CM}), provided a high enough luminosity can be obtained. In order to test the existence of Physics at the TeV scale, precisions of a few permil on the H(126) couplings to bosons and fermions are called for. Another way to test the existence of new physics beyond what could be observed directly at the High Luminosity LHC is to sharpen considerably the precision tests of the Electroweak Theory, i.e. the W and Z masses, the top quark mass, and Z peak observables such as the Z width, the polarization and charge asymmetries, the b partial width, etc... The TLEP physics programme benefits from three unique characteristics of the circular machines: i) high luminosity and reliability, ii) the availability of several interaction points, iii) superior beam energy accuracy. An e^+e^- storage ring of 80-km circumference can achieve transverse beam polarization at the Z peak and WW threshold, giving it unparalleled accuracy on the beam energy calibration by resonant depolarization. .

The luminosity of a storage ring collider rises linearly with its circumference, and, for a given tunnel size, rises linearly with the dissipated synchrotron radiation (SR) power. Therefore, the analysis can be scaled to different machine circumferences, including an existing tunnel like that of LEP/LHC. The energy reach depends strongly on the machine circumference. A preliminary study has shown that a 80 km tunnel is reasonably convenient around CERN. This allows good performance up to the t-tbar threshold (350 GeV E_{CM}), and would allow a proton-proton collider in the same ring to reach 100 TeV.

The accelerator

A first version of the parameters of TLEP has been produced (see Table 2 for the main parameters). The SR power has been fixed to 100MW. For a ring circumference of 80km a luminosity of 5 $10^{34}/cm^2/s$ is achieved for each of four IPs for E_{CM} = 240 GeV. The beam-beam tune shift has been taken to be 0.1 per IP from LEP2 experience. The gain of luminosity w.r.t. LEP2 is achieved by lowering the β^*_y to 1mm, and assuming top-up injection. If fewer experiments are assumed a higher luminosity per experiment should be achievable. Most of the components of the proposed superconducting RF system are readily available for frequencies around 700-800 MHz. A gradient of

20MV/m requires 900m of RF cavities distributed over four straight sections, giving an RF system size similar to that of LEP2. Higher accelerating gradients (35MV/m) lead to excessive power requirements for CW operation.

Wall Power For a wall-power to beam efficiency of the RF system of 55%, and taking into account the power needed by other systems (magnets, RF cryogenics, cooling, ventilation, injectors, experiments, general services) a very preliminary estimate of the total power consumption is around 320MW. This is a starting point. It will be one of the main objects of the study to maximize the luminosity/power ratio.

Cost A cost calculation of such a facility does not exist yet, but extrapolations from LEP are possible. The cost of the TLEP machine proper is estimated to be about 2BCHF, the largest item being the cost of the RF system. Initial estimates for the cost of the tunnel, which should be seen as an investment of the community as it can house the next suite of hadron/e-p/ion collider(s), is in the range 2.5-4.5BCHF. These are estimates assuming the CERN site (European accounting).

Beam lifetime and Beamstrahlung The performance of TLEP is obtained by operating at the beam-beam limit with a small value of β^*. Beam lifetime due to physics processes at the proposed luminosity is a few minutes at the high energies, calling for a 'top-up' scheme in a two ring design: the main storage ring collider operates at a constant energy, and the injector ring ramps continuously to top up the main ring every O(10-100) seconds. Beamstrahlung becomes a limitation, generating large energy loss of individual particles of one beam in the collective field of the other. The beam lifetime due to beamstrahlung needs to be kept larger than the top-up period. Since the beamstrahlung effect is inversely proportional to the beam size in x, the machine design aims to maximise the ratio of horizontal to vertical emittance (producing very flat beams at the IPs) together with a high momentum acceptance. Decreasing the vertical to horizontal emittance ratio by a factor of 4 reduces the required momentum acceptance by a factor of 2.

Challenges of such a collider lie in the design of the RF system (especially the power couplers), on reducing further the vertical emittance w.r.t. LEP2 to come close to the achievements obtained in light sources, and on high momentum acceptance optics to cope with beamstrahlung. Success of these developments will have direct impact on the luminosity-to-power ratio.

The physics reach TLEP can collect a total of 10 ab^{-1} in 5 years at 240 GeV E_{CM}; 1.4 ab^{-1} in 5 years at 350 GeV. TLEP operating in "Tera-Z" mode around the Z pole with luminosities of 10^{36} /cm^2/s can collect 10^{12} Z decays in one year (or 10^{11} with ~40% longitudinally polarized beams). At the W threshold in "Mega-W" mode (at 160 GeV E_{cm} and luminosity of 2×10^{35}) it can collect 10 Million W pairs in one year. The Physics performance goals are summarized in Table 1.

Beam Polarization Resonant spin depolarization can achieve an instantaneous precision of better than 100 KeV on the beam energy. Extrapolating from LEP2, transverse beam polarization should be available at TLEP for beam energies from the Z pole up to at least 80 GeV per beam. We envisage running with extra dedicated non-colliding bunches where polarization can build up and the energy measured continuously. This should allow measurements of the Z mass and width with a precision of 0.1 MeV or better and the W mass with a precision of 1 MeV or better. In addition, movable spin rotators as designed for HERA would allow a program of longitudinal polarized beams at the Z peak, resulting in a measurement of the beam polarization asymmetry with a precision of the order of 10^{-5} – or a precision on $\sin^2\theta_W^{eff}$ of the order of 10^{-6} for one year of data taking.

References

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Table 1 Sample of TLEP Physics performance goals

Physics region	E_{beam} (GeV)	E_{CM} (GeV)	Luminosity in each of 4 expts,	Beam Polarization	Physics goals
Z peak	44-47	88-94	10^{36} cm^{-2}s^{-1}	Transverse for energy calibration >5%	One year of data taking: $>3\times10^{11}$Z decays per experiment $>6\times10^{10}$ $\bar{b}$b pairs per experiment Z mass and width to 0.1 MeV/c^2 $\Delta\rho_\ell$ to $\leq 510^{-5}$; Improvements in R_{had} R_b Γ_{inv}, etc
Z peak	45.6	91.2	$>10^{35}$ cm^{-2}s^{-1}	Longitudinal,50%	A_{LR} A_{FB}^{Pol} ; $\sin^2\theta_w^{eff}$ to $\leq 310^{-6}$
W pair threshold and maximum	80-90	160-180	2.10^{35} cm^{-2}s^{-1}	Transverse for calibration >5%	One year of data taking: W mass to <1 MeV/c^2
ZH threshold and cross-section maximum	110-125	220-250	5.10^{34} cm^{-2}s^{-1}	Not required	5 years of data taking at ZH maximum (combined with 5 years at the $\bar{t}$t threshold). 2×10^6 ZH Events m_H (MeV) 7 $\Delta\Gamma_H / \Gamma_H$ 1.3% $\Delta\Gamma_{inv} / \Gamma_H$ 0.15% $\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$ 1.4% $\Delta g_{Hgg} / g_{Hgg}$ 0.7% $\Delta g_{Hww} / g_{Hww}$ 0.25% $\Delta g_{HZZ} / g_{HZZ}$ 0.2% $\Delta g_{H\mu\mu} / g_{H\mu\mu}$ 7% $\Delta g_{H\tau\tau} / g_{H\tau\tau}$ 0.4% $\Delta g_{Hcc} / g_{Hcc}$ 0.65% $\Delta g_{Hbb} / g_{Hbb}$ 0.22%
$\bar{t}$t threshold and High Energy (E_{CM}> 340 GeV)	170-180	340-360	7.10^{33} cm^{-2}s^{-1}	Not required	5 years of data taking: Top quark mass to 100 MeV/c^2 3.5 10^4 Hvv events

Table 2: Accelerator parameters

	TLEP – 90GeV	**TLEP – 240GeV**	**TLEP 350 GeV**
beam current [mA]	1180	24.3	5.4
#bunches/beam	2625	80	12
#e−/beam [10^{12}]	2000	40.5	9.0
horizontal emittance [nm]	31	9.4	20
vertical emittance [nm]	0.15	0.05	0.10
SR power/beam [MW]	50	50	50
β^*_x [m]	0.2	0.2	0.2
β^*_y [cm]	0.1	0.1	0.1
Hourglass factor	0.71	0.75	0.65
ΔE_{SR} loss/turn [GeV]	0.04	2.1	9.3
V_{RF} total	2	6	12
Accel. Gradient [MV/m]	20	20	20
ξ_x (ξ_y) per IP	0.12 (0.12)	0.10 (0.10)	0.05 (0.05)
Luminosity/IP[10^{32}cm^{-2}s^{-1}]	10400	490	65
Beam lifetime (bhabha) (4 IPs) [mins]	37	16	27